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RESEARCH MEMORANDUM

STARTING CHARACTERISTICS AND COMBUSTION PERFORMANCE OF MAGNESIUM SLURRY IN 6.5-INCH-DIAMETER RAM-JET ENGINE MOUNTED IN CONNECTED-PIPE FACILITY

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The starting characteristics and combustion performance of 50 percent magnesium powder in a hydrocarbon carrier were investigated in a flight-type, 6.5-inch-diameter ram-jet engine mounted in a connected-pipe facility. Starting disks, metal plates mounted in the combustion chamber and blocking part of the burner area, were developed that provide quick, dependable starting of the engine over the starting equivalence ratio range investigated, 0.36 to 0.69. After the engine was started, the disk was expelled to permit normal operation of the engine. One of the disks was expelled within 0.1 second after fuel-flow initiation. No explosive starts were experienced. A flame-holder protection plate, designed to cover the cavity in the flame-holder mounting tube, permitted operation without flame-holder damage for test durations of about 20 seconds. The combustion tests were made with a short, 8.5-inch fuel-air mixing length, because combustion instability was encountered in previous free-jet tests with a longer mixing length. The combustion efficiency was above 77 percent for the equivalence ratio range from 0.5 to 1.0 and reached a maximum of 81 percent at an equivalence ratio of 0.7. Increases in inlet-air temperature from about 60° to 370° F caused increases in combustor efficiency of 12 to 22 percent over the equivalence ratio range investigated.

Performance data obtained with the slurry system having the short fuel-air mixing length were compared with performance data obtained in the free-jet and flight tests of similar ethylene-fueled ram-jet engines at the NACA Langley laboratory. The slurry fuel provided over twice the fuel volume specific impulse; however, the fuel weight specific impulse was slightly higher for the ethylene fuel. An air specific impulse of 187 seconds was obtained with the slurry fuel, while the maximum obtained with ethylene was 159 seconds. In the Langley flight-test vehicle, a greater fuel load and a greater thrust would be possible if the ethylene fuel were replaced by a magnesium slurry. Therefore, higher flight speeds, higher altitudes, and longer flight durations should be attainable with the slurry fuel.

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INTRODUCTION

As part of a high-energy-fuels program at the NACA Lewis laboratory, the combustion performance of a magnesium slurry was investigated in a 6.5-inch-diameter ram-jet engine mounted in a connected-pipe facility (ref. 1). The fuel consisted of 50 percent atomized magnesium powder by weight suspended in a hydrocarbon carrier fuel. The slurry performance was compared with the performance of ethylene in free-jet (ref. 2) and flight (refs. 3 and 4) tests of similar ram-jet engines. As a result, appreciable performance gains were predicted for the slurry system over the ethylene-fueled, supersonic-flight vehicle described in reference 3. 3091

The slurry-engine combination is being preflight tested in the free-jet facility at the NACA Wallops Island, Virginia station. In the initial tests, flame holder and combustor failures were encountered because of intermittent combustion upstream of the flame holder. Since the two types of testing differed mainly in the method of air diffusion, the unstable combustion in the free-jet was believed to have been caused by a more irregular velocity profile near the station of fuel injection than was present in the connected-pipe tests. In subsequent free-jet tests, the fuel injection station was moved downstream $3\frac{1}{2}$ inches to a region with a more regular velocity profile. The combustion upstream of the flame holder was eliminated; however, the shortened fuel-air mixing length resulted in performance lower than that predicted from the connected-pipe tests for equivalence ratios greater than about 0.6. Throughout these tests, the engine starting characteristics were erratic with the flare ignitor used in the connected-pipe tests. In addition, flame-holder life with stable combustion was considered marginal.

The present investigation was directed toward improving the starting characteristics of the engine, increasing flame-holder durability, and increasing the combustion performance at high equivalence ratios while using a fuel-air mixing length $3\frac{1}{2}$ inches shorter than that reported in reference 1. A series of short combustion tests was conducted with a 50 percent magnesium slurry in a ram-jet engine similar to that used in reference 1 in a connected-pipe facility. A disk, blocking part of the burner area, was mounted in the combustion chamber as an engine-starting aid. The disk was designed to provide high combustor pressures and low velocities downstream of the flame holder prior to ignition and then to fail from mechanical stresses at elevated temperatures shortly after ignition. Seven design variations of the starting disk were studied, and the effects of three fuel-distribution control-sleeve configurations on combustion performance are compared. Also, the effects of inlet-air temperature on performance and of a flame-holder protection plate on combustion performance and flame-holder durability are described.

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FUEL AND APPARATUS

Fuel. - The fuel contained equal parts by weight of magnesium powder and a hydrocarbon fuel. An analysis of the hydrocarbon carrier, MIL-F-5624A grade JP-4 fuel, is given in table I. Currently, only a limited amount of small-particle-size magnesium is available; this material is stored in drums and the purity of the powder varies from one drum to another. In order to conserve the purer powder for preflight and flight testing, the powder used in this investigation was obtained from those drums containing the greatest amount of impurities. This material was made into two 200-pound batches of slurry and representative samples of each batch were analyzed. In each case the purity of the powder was measured at 93 ±1 percent. Thus, the ratio of actual uncombined magnesium to magnesium plus hydrocarbon was 0.48, the stoichiometric fuel-air ratio was 0.1109, and the lower heat of combustion was 14,900 Btu per pound of magnesium plus hydrocarbon. The slurry density including impurities was measured at 1.05 grams per cubic centimeter, the same value as computed for a 48-percent-pure magnesium slurry. The mean size of the nearly spherical powder particles was 1.5 microns as determined with a Fisher Sub-Seive Sizer. Because of the small powder size, the slurries were stable (apparently homogeneous) for over 24 hours, and for this investigation no stabilizing additives were required.

Fuel system and ram-jet installation. - A diagram of the fuel system is shown in figure 1. Fuel was supplied to the engine from a 2-cubic foot fuel tank pressurized with nitrogen. The rate of fuel flow was governed by the flow-restricting orifice located upstream of the fuel injectors and by the controlled fuel-tank pressure. The maximum fuel-tank pressure was 260 pounds per square inch gage.

A diagram of the ram-jet installation is also shown in figure 1. The combustion air, from the laboratory air supply, was passed through a tube-type heat exchanger, metered, and then throttled by a remotely controlled butterfly valve. The combustor shell was cooled by diverting a fixed portion (approx. 36 percent) of the combustion air through a 1/2-inch annulus between the shell and a cooling jacket. The high external pressure of the cooling air on the combustor necessitated the use of four longitudinal reinforcement bars and a combustor shell thickness of 0.093 inch. The cooling air recombined with the main portion of the combustion air in the inlet plenum and then entered the engine. A 3-foot-long shroud was mounted on the ram-jet diffuser lip in an effort to obtain a flat velocity profile at the entrance to the diffuser. The combustion products were discharged into the atmosphere just outside the test cell.

Ram-jet engine. - A detailed description of the basic engine is presented in reference 3. A diagram of the engine, as modified for the present investigation, is shown in figure 2. The diffuser-lip diameter was 4.42 inches. The inside diameter and the length of the Inconel combustor

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were 6.5 and 19 inches, respectively. The exhaust nozzle was 6 inches in diameter.

The inner body of the basic engine of reference 3 was modified immediately downstream of the support struts to accomodate the slurry injector and the flame holder. A spring-loaded variable-port-area injector, having four longitudinal slots spaced 90° apart, is shown in figure 2. The piston area and the spring were designed to provide a pressure drop of about 50 pounds per square inch across the fuel slots for the fuel-flow-range investigated. An O-ring seal and silicone grease were used to prevent seizing of the piston. Atomization of the fuel was achieved by impinging the fuel jets on a cylindrical fuel-distribution control sleeve mounted in the air stream. The fuel slots were located $8\frac{1}{2}$ inches from the face of the flame holder (fig. 2). The flame holder was composed of V-gutters and funnels (surfaces of revolution of a cone), and it blocked 46 percent of the combustor cross-sectional area. The material used for the flame holder was 3/32-inch-thick Inconel. The aforementioned fuel injector and flame holder gave the best performance of the several types tested during the development program described in reference 1; however, the distance from the fuel injection slots to the flame-holder face (fuel-air mixing length) was 12 inches in the investigation reported in reference 1.

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Ignition was provided by a magnesium flare 4 inches long and 2 inches in diameter with a nominal burning time of 20 seconds. The flare was cemented into a 1/16-inch-wall Inconel tube which fitted into the flame-holder cavity (fig. 2). The downstream (ignition) face of the flare was coincident with the downstream edge of the flame holder.

Starting disks. - A total of seven design variations of starting disks of two general types were studied. The two types differed only in the location of the disk in the combustion chamber and the method of mounting. Diagrams of both types and a table listing the dimensions are shown in figure 3. The flame-holder-mounted disks, numbers 1, 2, 3, and 4, were located near the center of the combustion chamber and were held in place by means of straps hooked over the funnel part of the flame holder. The nozzle-mounted disks were slipped edgewise in the nozzle at the disk flats, turned, and butted against the upstream edge of the nozzle. A nozzle mounted disk is shown in position in figure 2.

Instrumentation. - The combustion air flow was measured by a square-edge orifice conforming to A.S.M.E. standards. The orifice differential pressure and the combustor static pressure at station 8 (fig. 2) were sensed by Statham pressure pickups and recorded continuously on a four-channel oscillograph. The frequency response of the electrical portion of the system was flat up to 25 cycles per second. However, for convenience, the combustor static-pressure tap and sensing element were physically separated so that an appreciable time lag was noted in this

measurement. The combustion-air-orifice upstream pressure was recorded at 2-second intervals by means of a pressure pickup and a self-balancing potentiometer.

The fuel-flow rate was metered by means of a rotating-vane flowmeter and an indicating potentiometer. This measurement was checked with Bourdon gages which indicated the pressure drop between the fuel tank and a point downstream of the restricting orifice (fig. 1).

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The orifice and combustor-inlet air temperatures were measured with a recording potentiometer at 12-second intervals.

PROCEDURE

The two fuel flowmeters and the pressure-recording equipment were subjected to a comprehensive calibration approximately every 6 runs. An additional check on the air-orifice and combustor pressures was made prior to each run by obtaining steady-state data at several air flows and comparing the record data to manometer and gage readings. The absolute accuracy of the measured values is believed to be within ±3 percent.

The slurry was transferred to the fuel tank immediately after mixing by pressurizing the mixing barrel with nitrogen. In order to ensure that the fuel in the tank was nearly homogeneous, the runs were usually made within 2 hours after filling the tank. If a greater period of time elapsed after the tank was filled, the fuel tank was removed from the apparatus and agitated on a barrel roller prior to the run.

A small quantity of heated combustion air was passed through the apparatus before each high-inlet-air-temperature run to permit the inlet-air ducting to approach equilibrium temperature. Pressure was applied to the fuel tank and the recorder-chart drives were turned on. In the flight vehicle, the flare is ignited before the vehicle is launched; therefore, the flare was ignited at low air-flow rates in this investigation. The air flow was then rapidly increased to the starting condition, whereupon the fuel valve was opened. From this point, two procedures were followed: In the initial tests, emphasis was placed on the engine starting characteristics, and the fuel valve was turned off within 5 seconds after the start of the test. The fuel and air flows remained nearly constant throughout these tests. In the later tests, the air flow was changed in steps of about 5-seconds' duration in order to cover a range of fuel-air ratios. The fuel flow changed slightly during the later tests because of a changing combustor pressure.

After the run, the fuel system downstream of the fuel tank was drained and flushed with gasoline. The flame holder and the fuel injector were removed, cleaned, and inspected for material failure and oxide deposits.

DATA REDUCTION

In order to allow as much time as possible for the combustor and the instrumentation to reach equilibrium before data were recorded, data points were chosen from the records at each air flow near the start of the next step air-flow change.

The fuel performance was evaluated by computing the air specific impulse, fuel weight specific impulse, and fuel volume specific impulse. These parameters express the total stream momentum per unit weight of air, per unit weight of fuel, and per unit volume of fuel, respectively, referenced at the exhaust-nozzle throat for a Mach number of 1. They are defined by the following expressions: 3091

$$\text{Air specific impulse} = \frac{\text{Total stream momentum}}{\text{Air flow}} \quad \frac{(\text{lb})(\text{sec})}{(\text{lb})}$$

$$\text{Fuel weight specific impulse} = \frac{\text{Air specific impulse}}{\text{Fuel-air ratio}} \; (\text{sec})$$

$$\text{Fuel volume specific impulse} \left(\frac{\text{lb-sec}}{\text{cu ft}}\right)$$

$$= \text{Fuel weight specific impulse} \times \text{Fuel density}$$

Figure 7 of reference 1 shows a straight-line relation between the total stream momentum, determined by means of a thrust barrel, and the combustor static pressure at station 8; the data scatter was less than ±3 percent of the mean when the exit nozzle remained nearly free of oxide deposits. Since in the present investigation, the range of operating conditions and the fuel were similar to, and the combustor and the combustor static-pressure-tap location were identical to those used in reference 1, the stream momentum was conveniently determined by means of the measured combustor-exit static pressure.

The combustor efficiency for each datum point was determined by

$$\text{Combustor efficiency (percent)} = \frac{\text{Fuel-air ratio, ideal}}{\text{Fuel-air ratio, actual}} \times 100$$

at constant air specific impulse. An efficiency defined in this manner includes exit-nozzle efficiencies and the heat losses to the burner walls as well as the combustion efficiencies based on the enthalpy rise across the combustor. The ideal values of equivalence ratio were obtained from references 6 and 7 for the proper inlet temperature and a combustor pressure of 2 atmospheres. Because of the impurities in the magnesium powder used to prepare the nominal 50 percent slurry, each pound of the fuel

actually consisted of 0.5 pound of JP-4, 0.465 pound of magnesium, and 0.035 pound of impurities. This mixture is equivalent to 0.965 pound of a 48 percent slurry and 0.035 pound of impurities. Therefore, to compute realistic combustor efficiencies, it was necessary to multiply the fuel flow rate by a factor of 0.965 to obtain the flow rate of the "pure fuel." It was also necessary to use ideal equivalence ratios based upon air-specific-impulse data for the actual uncombined magnesium concentration, 48 percent. These two corrections affect the computed combustor efficiencies in opposite directions, and the net effect is that the values reported herein are about 2 percent higher than the values would have been if the fuel impurities had been ignored.

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RESULTS AND DISCUSSION

Starting Characteristics

The engine starting difficulties encountered in the free-jet tests, which simulate flight-test starting conditions, were probably caused by the use of higher air-flow rates and, therefore, combustor velocities higher than those used in the connected-pipe tests reported in reference 1. In order to achieve the higher air flows in the present investigation with the available air supply, low inlet-air temperatures were used for the initial series of tests. Although the low inlet temperatures do not simulate the flight-test starting condition, the resulting starting condition created a combustion environment which was as severe as could be achieved with the existing test apparatus and was adequate to determine the beneficial effect of a starting aid.

The significant results of all the starting tests are presented in table II. The engine started without a starting disk in the first test, where the maximum air flow was 14.2 pounds per second and the inlet-air temperature, 300° F. In the second test, the temperature was reduced to 135° F and the open-throttle air flow was 18.4 pounds per second. The engine did not start at this condition without a starting aid. It was assumed that the engine would not start without aid at combustor-inlet conditions near, or more severe than, those of run 2.

Flame-holder-mounted starting disks. - Starting disks 1, 2, 3, and 4 (fig. 3) were fastened to the flame holder by straps, and the disks were axially located near the central part of the combustion chamber. The central location was chosen in order to reduce the quantity of fuel in the combustion chamber at the time of ignition and thereby to reduce the possibility of explosive starts. A typical start with a flame-holder-mounted disk is shown in figure 4(a) which is a photograph of the orifice-air pressure differential Δp and the combustor-exit static-pressure traces. A possible criterion of engine starting is the time required from fuel flow initiation (time zero) to the point where the engine is operating

at full thrust. Full thrust was assumed to be the point where the combustor-exit pressure rose to the maximum steady state at the starting conditions. Since the exact point of full thrust or full combustor-exit pressure was difficult to determine because of the slope of the pressure trace, a more reproducible engine starting criterion was the time required to achieve 90 percent of full thrust. Both the time to full thrust and the time to 90 percent of full thrust are listed in table II for the tests without a starting disk and for those with flame-holder-mounted disks.

As indicated in table II starting disks 1 and 2 (fig. 3) failed either 3091
at the straps or at the fastening between the straps and disks prior to ignition during 3 of the 12 start tests. The number of fasteners was increased for starting disk 3 and the starting aid provided satisfactory ignition in four tests covering a range of equivalence ratios from 0.58 to 0.69. The 69 percent blocked area of starting disk 3 was reduced to 57 percent for starting disk 4, and essentially the same time to 90 percent and 100 percent full thrust was obtained for starting disk 4 as for 3. The starting results indicated that disks 3 and 4 would be satisfactory; however, the nature of failure of one of the flame-holder-mounted disks tested, disk 2, indicated a potential hazard in the use of this type of starting aid. In this test the straps on only one side of disk 2 failed; this allowed the disk to flop over to one side of the combustor out of the active burning zone. The resultant combustor performance was low during the entire 4-second-duration run presumably because of the skewed flow resulting from the lingering disk. Since there was no guarantee against the recurrence of this type of failure, exit-nozzle-mounted disks were next considered.

Exit-nozzle-mounted starting disks. - The exit-nozzle-mounted disks, numbers 5, 6, and 7, were held in place at the upstream edge of the exit nozzle by the air forces. In the runs with nozzle-mounted disks, the combustor-exit pressure tap was upstream of the disk rather than downstream; therefore, the combustor pressure upstream of the disk rose to a peak after ignition then dropped to the steady-state full-thrust value. The time from fuel-flow initiation to disk expulsion, which occurred at the peak combustor pressure, was used as an engine starting criterion and is listed along with the peak pressure for all tests in table II. A photograph of the combustor pressure and the orifice pressure-drop traces during a typical start with a nozzle mounted disk is shown in figure 4(b).

Disk 5 (fig. 3) was not strong enough to resist the force of the air prior to ignition. Disk 6 was made thicker and of harder aluminum. No start failures were encountered with disk 6 in six tests covering a range of equivalence ratios from 0.36 to 0.57 and a range of air flows from 13.1 to 18.7 pounds per second. The maximum time required to expel disk 6 in the six tests was 0.8 second. This time was not excessive but, in free-jet or flight tests, the required peak combustor pressure would not be reached because of diffuser buzz, and the time to expel a given

disk might be increased. Therefore, disk 7 was designed with a thickness of 3/32 inch instead of the 1/8 inch thickness of disk 6. This disk was able to withstand air flows at least up to 18 pounds per second during a cold test and was expelled in 0.1 second during a start test (run 31, table II). No explosive starts were experienced throughout the investigation.

Exit-nozzle-mounted disks are recommended for the flight vehicle since their complete expulsion is more certain than is that of the flame-holder-mounted disks. Disk 7 was expelled very rapidly after ignition and yet had adequate strength to withstand the air flow forces anticipated at the proposed flight starting conditions; this disk is therefore recommended for the current flight vehicle.

Combustion Performance

This part of the investigation was directed toward improving the combustion performance of the slurry-fueled combustor, developed in the investigation reported in reference 1, by using a modified fuel-air mixing length of 8.5 inches instead of the 12-inch length used in reference 1. Because of the performance characteristics of the slurry fuel and the particular flight application proposed, emphasis was placed on improving the rich performance, for example, performance at equivalence ratios above 0.5. The requirements for the flight application were a combustor that would exhibit higher thrusts (air specific impulse) and more desirable fuel consumption than the ethylene combustor at the following conditions: combustor-inlet pressure, 30 to 60 pounds per square inch absolute; inlet-air temperature, approximately 350° F; exit-nozzle throat diameter, 6.0 inches. The results of all tests in which combustion was achieved are presented in table III, and the significant results are discussed in the following paragraphs.

Oxide deposits. - The oxide deposits in these tests are significant with respect to both projected flight performance and interpretation of the performance data reported herein. Because the performance data are expressed in terms of air specific impulse and are dependent upon the exit-nozzle area and nozzle pressure data, the combustor was carefully checked after each run. No deposits were found in the nozzle throat or blocking the combustor-exit static pressure tap and only thin scaly oxide deposits were found on the combustor walls.

Effect of inlet-air temperature. - The effect of inlet-air temperature on the combustion efficiency of the combustor configuration with a fuel-distribution control sleeve 2 inches long and 4 inches in diameter and a flame-holder protection plate is shown in figure 5. Approximately 15 to 20 percentage points in combustion efficiency were gained by increasing the combustor inlet-air temperature from 63° to 367° F over the range of equivalence ratios investigated.

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Effect of flame-holder protection plate on flame-holder durability and performance. - The flame-holder design incorporates a flare mounted in the rear of the centerbody. Observations made in the investigation reported in reference 1 and in the present investigation indicated that the failures which originated in the rear part of the flare-holder case and the flame-holder mounting tubing progressed forward with a resultant failure to the flame-holder section. It was considered advisable to restrict the open area at the end of the flare-holder tube in order to minimize the recirculation of combustion products in the critical area. This was attempted by the use of a flame-holder protection plate which 3091
consisted of an Inconel cap containing a 3/4-inch-diameter hole for the discharge of the flare flame. When the flame-holder protection plate was used in the short tests, 20 seconds or less, damage to the flame-holder section was negligible although the protection plate was burned away in all tests that exceeded 10 seconds.

In the tests of about 25 seconds, damage to the flame holder was beginning as evidenced by declining performance level in the last few seconds of one of the tests. Examination of the combustor after the test also indicated the start of flame-holder damage. The use of a flame-holder protection plate permitted "failure free" operation in the short tests up to 20 seconds in duration.

In the four tests made without a flame-holder protection plate at the low inlet temperatures, the performance was lower than in the tests made with a protection plate (fig. 5). However, in the two tests with a protection plate at the higher inlet temperature, the protection plate was burned away during the tests without noticeably affecting the performance. This indicates that performance is unaffected by the use of the protection plate at the high inlet temperatures which simulate flight conditions.

Effect of fuel-distribution control-sleeve length and diameter. - A loss in performance at high equivalence ratios was experienced in the free-jet tests when, in order to improve combustion stability, the fuel-air mixing length was reduced from 12.0 to 8.5 inches. Part of the loss was probably caused by the decreased length available for fuel spreading which in turn caused a fuel rich region near the flame-holder center. Therefore, the fuel-distribution control-sleeve dimensions were varied in an effort to regain the performance lost. Combustion efficiency is plotted as a function of equivalence ratio in figure 6 for three fuel-distribution control-sleeve configurations. For the 8.5-inch fuel-air mixing length, considerable increases in performance were achieved by reducing the control-sleeve length from $4\frac{1}{2}$ to 2 inches; the largest gains occurred in the low-equivalence-ratio region. Further improvements at the higher equivalence ratios resulted when the fuel-distribution control-sleeve diameter was increased from 4 to $4\frac{1}{2}$ inches. Both of these changes cause

the fuel to be distributed further from the flame-holder center. The combustor efficiency was above 77 percent for the equivalence ratio range from 0.5 to 1.0 and reached a maximum of 81 percent at an equivalence ratio of 0.7. This performance is considered acceptable for initial flight tests.

An absolute comparison of the effect of fuel-air mixing length is impossible because the combustor evaluated in reference 1, although similar to the combustor tested in this investigation, had a different fuel-air mixing length, flame-holder protection plate, and fuel. As previously discussed, the effect of a flame-holder protection plate on combustion performance at an inlet-air temperature of approximately 340° F was negligible. The fuel used in this investigation, although of lower purity, was of smaller particle size than the fuel used in reference 1 and, because of the effect of particle size on the combustion performance reported in reference 8, would probably be more reactive than the fuel used in reference 1. Comparison of the combustor efficiency curves presented in figure 6 for fuel-distribution control sleeves $4\frac{1}{2}$ inches long and 4 inches in diameter shows that a considerable loss in performance results when the fuel-air mixing length is reduced from 12 to 8.5 inches. The major part of this performance loss was recovered by reducing the control-sleeve length to 2 inches and increasing the diameter to $4\frac{1}{2}$ inches.

Comparison of Slurry and Ethylene Performance

The performance of slurry fuel in the best configuration with the 8.5-inch fuel-air mixing length was compared with the performance of ethylene fuel in free-jet tests of a similar ram-jet (ref. 2). The slurry performance was obtained from figure 6 for the 2-inch-long, $4\frac{1}{2}$-inch-diameter, fuel-distribution control sleeve. The diffuser was immersed in a supersonic air stream in the free-jet tests, and this may have resulted in combustor-inlet velocity profiles different from those encountered in the present connected-pipe tests. Variations in velocity profile, by affecting the mixing of the fuel and air, could influence the combustion performance. The diffuser-entrance and nozzle-throat diameters for the ethylene tests were 3.96 and 5.75 inches, respectively, as compared to 4.42 and 6.0 for the slurry tests. Consequently, the combustor velocities associated with the ethylene data were lower than those reported for the slurry tests.

Comparison of fuel weight and air specific impulse data. - Fuel weight specific impulse is plotted against air specific impulse for slurry and for ethylene fuels (fig. 7(a)). The ideal performance data for the slurry and octene-1 fuels were obtained from reference 6 and for ethylene from reference 9. Over the range of air specific impulse obtained with

ethylene, the fuel weight specific impulse of ethylene was greater than that of the slurry. However, the experimental curves tend to converge as the fuel-air ratio was increased. At an air specific impulse of 159 seconds, which was the maximum obtained with ethylene, the fuel weight specific impulse of the ethylene and the slurry were 2350 and 1950 seconds, respectively. In short-range-flight applications, the fuel weight represents a very small fraction of the total vehicle weight and the lower fuel weight specific impulse values obtained at low thrust levels is therefore of secondary importance. The thrust determines the attainable flight speed and altitude; the higher thrust levels obtainable with slurry fuel is therefore of primary importance. The slurry fuel permitted operation up to an air specific impulse of 187 seconds. 3091

Comparison of fuel volume and air specific impulse data. - Fuel volume specific impulse, which is a measure of the volume of fuel consumed, is presented on figure 7(b) as a function of the air specific impulse. A density of 18.3 pounds per cubic foot was used for the ethylene volume impulse computation. This density was obtained when the flight fuel tank was pressurized to 1200 pounds per square inch. The fuel volume specific impulse of the slurry was 2.6 and 2.9 times that of ethylene at air specific impulses of 140 and 159 seconds, respectively. At air specific impulse values of 150 to 170, the experimental fuel volume impulse of the slurry was about 10 percent lower than the ideal volume impulse for octene-1.

The fuel volume specific impulse is a significant parameter when applied to vehicles that have a small ratio of fuel weight to gross vehicle weight. For example, the Langley flight vehicle had an ethylene fuel to gross weight ratio of 0.1. Hence, a large increase in volume specific fuel consumption can make possible a correspondingly large increase in fuel load with only a small increase in vehicle gross weight.

SUMMARY OF RESULTS

1. The results obtained with a 50 percent magnesium slurry fuel in a flight type, 6.5-inch-diameter ram-jet engine in a connected-pipe facility are as follows:

a. Starting disks, mounted in either the central or exit stations in the combustor, provided quick, dependable starting of the engine over the equivalence ratio range investigated, 0.36 to 0.69. A disk mounted in front of the exit nozzles was expelled within 0.1 second after fuel flow initiation. No explosive starts were experienced.

b. A flame-holder protection plate which covered most of the flare-holder tube cavity prevented damage to the flame holder during

tests of 20 seconds' duration or less. Slight damage occurred in two tests of longer duration. Without the protection plate, appreciable flame-holder damage occurred during a test duration of 3 seconds.

c. A short, 8.5-inch fuel-air mixing length was used in order to eliminate the intermittent combustion upstream of the flame holder which had been experienced in previous free-jet tests of the engine. The short mixing length resulted in an appreciable decrease in combustion efficiency from values previously achieved with a longer mixing length. The greater part of this performance loss was recovered, however, by redesigning the fuel-distribution control sleeve. The combustor efficiency for the best configuration with the 8.5-inch mixing length was above 77 percent for the equivalence ratio range from 0.5 to 1.0 and reached a maximum of 81 percent at an equivalence ratio of 0.7.

d. An increase in average inlet-air temperature from 63° to 367° F increased the combustor efficiency from 56 to 78 percent at an equivalence ratio of 0.5, and the increase was from 58 to 70 percent at an equivalence ratio of 1.0.

2. The following results compare the performance of the slurry fuel in the short, 8.5-inch fuel-air mixing length with that of ethylene fuel, both evaluated under similar conditions. The ethylene data were obtained from free-jet tests of a ram-jet engine designed for a flight-test vehicle at the NACA Langley laboratory.

a. The fuel volume specific impulse of the slurry was 2.6 and 2.9 times that of ethylene at air-specific-impulse values of 140 and 159 seconds, respectively.

b. The maximum air specific impulse obtained with the slurry and with ethylene were 187 and 159 seconds, respectively.

c. The fuel weight specific impulses of ethylene and slurry fuels were 2350 and 1950 seconds, respectively, for the maximum air specific impulse obtained with ethylene, 159 seconds.

CONCLUSIONS

A starting disk was developed which is recommended for use in a proposed NACA Langley flight-test vehicle. The disk provided reliable starting of the engine and was expelled rapidly after ignition.

In the Langley flight-test vehicle, a greater fuel load and a greater thrust would be possible if the ethylene fuel were replaced by a magnesium

slurry. Therefore, higher flight speeds, altitudes, and longer flight durations should be attainable with the slurry fuel.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 9, 1953

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TABLE I. - ANALYSIS OF HYDROCARBON CARRIER FUEL

Fuel properties	MIL-F-5624A grade JP-4
A.S.T.M. distillation D86-46, °F	
Initial boiling point	140
Percent evaporated	
5	199
10	222
20	248
30	268
40	286
50	300
60	325
70	348
80	382
90	427
95	459
Final boiling point	488
Residue, percent	1.0
Specific gravity	0.768
Reid vapor pressure, lb/sq in.	2.5
Hydrogen-carbon ratio	0.167
Net heat of combustion, Btu/lb	18,675

TABLE II. - SUMMARY OF STARTING TESTS FOR 6.5-INCH-DIAMETER RAM-JET ENGINE

[Slurry: 50 percent magnesium powder in MIL-F-5624A grade JP-4 fuel]

Run	Disk	Inlet-air temperature, °F	Combustion air flow, lb/sec	Equivalence ratio	Time to percent of full thrust, sec		Time to expel start disk, sec	Peak combustor-exit static pressure, lb/sq in. abs	Remarks
					90	100			
1	None	300	14.2	0.68	0.9	1.8			Start without disk
2	None	135	18.4	.55	No start				No start
3	1								One start failure in four attempts. Disk-holding straps failed
4									
5									
6									
7	2								Two start failures in eight attempts. Fasteners holding disk to straps failed
8									
9									
10									
11									
12									
13									
14									
15	3	78	15.3	0.69	1.3	2.3			
16		76	17.3	.58	1.1	1.6			
17		76	15.8	.67	1.1	2.2			
18		75	16.2	.65			*	*	*Lost combustor-pressure trace
19	5								Disk failed mechanically prior to fuel flow initiation in each attempt
20									
21									
23	4	72	17.4	0.57	1.3	2.0			
24	6	68	18.7	0.53			0.1	53	
25		66	18.2	.53			.4	68	
26		63	18.1	.56			.2	63	
27		375	13.7	.36			.8	69	
28		360	13.1	.48			.7	70	
29		350	13.7	.54			.5	62	
30	7	365	12.7	0.52			-*	57	*Instrument-chart drive not on at start of run
31		337	13.2	.51			0.1	55	

TABLE III. - SUMMARY OF COMBUSTION DATA FOR 6.5-INCH-DIAMETER RAM-JET ENGINE

[Slurry: 50 percent magnesium powder in MIL-F-5624A grade JP-4 fuel]

Run	Flame-holder protection plate	Length of fuel control sleeve, in.	Diameter of fuel control sleeve, in.	Inlet-air temperature, °F	Time from fuel flow initiation, sec	Combustion air flow, lb/sec	Equivalence ratio	Combustor-exit static pressure, lb/sq in. abs	Air specific impulse, sec	Combustor efficiency, percent	After run observations: Protection-plate damage	After run observations: Flame-holder damage
5	Yes	2	4	85	1.7	19.80	0.46	47.5	106	0.47	None	None
7	Yes	2	4	80	1.6	17.40	.57	52.9	129	.62	None	None
8	No	2	4	82	.9	17.10	.61	46.6	118	.47		(a)
11	Yes	2	4	83	1.5	10.40	1.15	38.9	161	.48	None	None
12	No	2	4	88	1.3	11.70	1.03	36.9	154	.40		
				84	2.8	11.30	1.06	38.5	149	.60		
13	Yes	2	4	84	1.8	13.70	0.77	46.7	143	0.63	None	
15	Yes	2	4	78	2.5	14.80	.77	48.3	145	.68		
16	Yes	2	4	78	2.7	16.80	.80	52.3	138	.66		
17	Yes	2	4	78	2.2	15.00	.70	42.8	141	.66		
19	Yes	2	4	72	1.7	15.20	.58	51.5	144	.71		
					3.4	14.90	.70	53.3	152	.81		
20	Yes	2	4	75	2.4	12.80	0.67	44.8	161	0.64	None	
22	No	2	4	69	2.2	15.70	.75	43.1	117	.40		
23	Yes	2	4	72	2.0	16.70	.58	51.9	132	.66	None	
24	Yes	2	4	68	.4	17.70	.58	52.7	128	.62		
					4.0	16.80	.60	50.9	131	.64		
25	No	2	4	68	1.9	16.00	.62	47.5	126	.58		
26	Yes	2	4	63	1.3	17.30	0.58	52.6	129	0.63	Cracked, about 1/4 segment was burned away	
					4.8	16.00	.64	50.0	133	.63		
				64	5.6	13.70	.75	46.7	144	.65		
					7.4	12.80	.80	44.0	145	.62		
					8.6	11.70	.89	41.9	152	.63		
				65	9.7	10.80	.97	40.0	156	.63		
27	Yes	2	4	575	2.8	12.55	0.40	36.8	134	0.74	Burned away	
					5.2	12.30	.41	37.6	135	.74		
					8.0	10.60	.47	36.1	139	.67		
					11.0	8.06	.65	31.0	152	.63		
					12.7	7.80	.82	30.4	158	.62		
					15.0	6.13	.95	28.2	166	.72		
					16.7	6.06	.96	24.8	168	.71		
28	Yes	2	4	380	2.3	12.90	0.48	42.9	128	0.78		
					4.7	12.70	.48	41.8	138	.78		
					8.8	8.07	.80	31.8	160	.77		
					12.0	6.88	1.06	28.4	169	.68		
					14.4	6.05	1.25	28.5	171	.60		
					16.0	5.38	1.40	25.7	178	.62		
29	Yes	$4\frac{1}{2}$	4	350	3.0	13.90	0.58	41.0	132	0.84		
					7.0	11.80	.65	38.2	144	.73		
					11.0	9.16	.66	34.4	169	.70		
					14.0	10.86	.70	38.1	148	.71		
					17.0	9.77	.80	36.9	156	.71		
					20.0	12.70	.57	40.0	137	.69		
30	Yes	$4\frac{1}{2}$	4	365	2.0	12.86	0.51	41.0	137	0.78		(b)
					6.5	12.44	.53	40.1	137	.74		
					10.0	10.80	.62	37.0	145	.74		
					14.0	9.25	.74	33.6	154	.75		
					15.5	9.44	.73	34.0	153	.75		
					18.5	7.08	1.02	28.2	169	.70		
					22.5	6.11	1.21	24.9	172	.63		
					26.5	12.32	.55	41.2	148	.78		
31	Yes	2	$4\frac{1}{2}$	337	3.0	12.94	0.52	42.0	138	0.77		(c)
					8.0	10.11	.70	37.1	156	.61		
					13.0	8.06	.90	31.8	168	.78		
					16.0	6.32	1.18	26.7	178	.74		
					21.6	4.71	1.64	20.8	187	.64		
					25.0	12.40	.55	38.1	134	.67		

[a]Tube severely burned.
[b]Slight damage to tube.
[c]Two vanes burned away.

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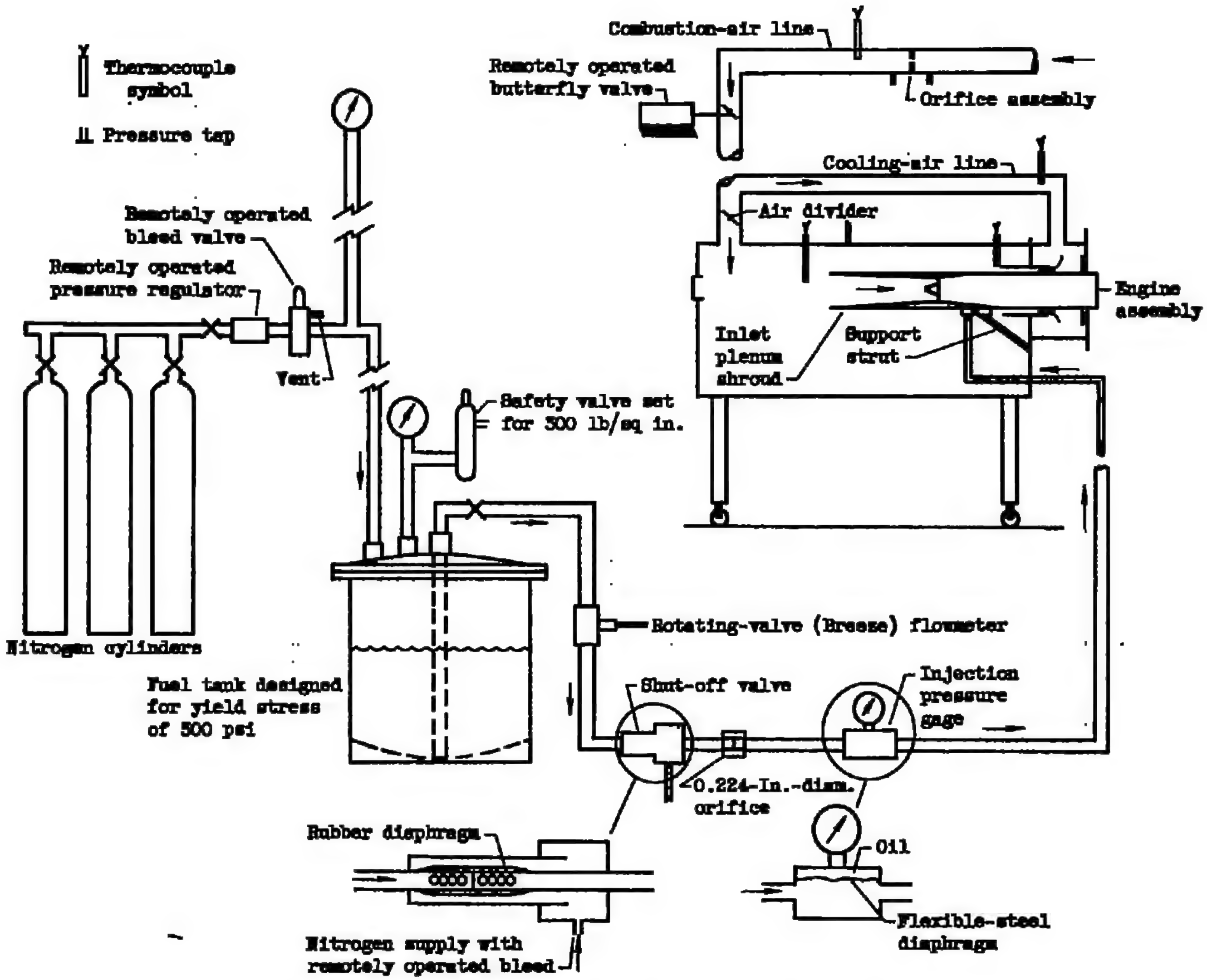

Figure 1. - Diagram of fuel system and ram-jet engine installation.

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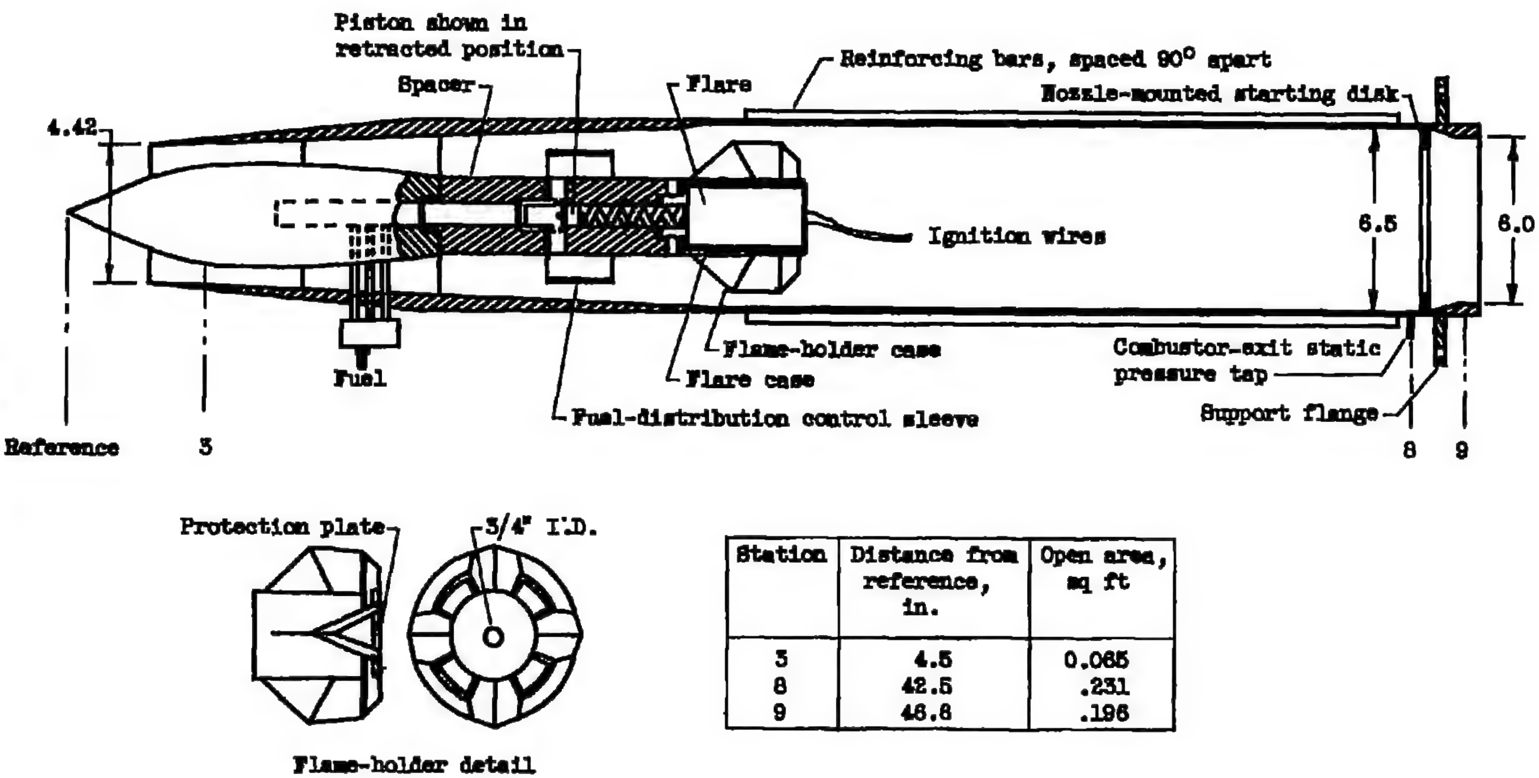

Station	Distance from reference, in.	Open area, sq ft
3	4.5	0.065
8	42.5	.231
9	46.8	.196

Figure 2. - Ram-jet engine.

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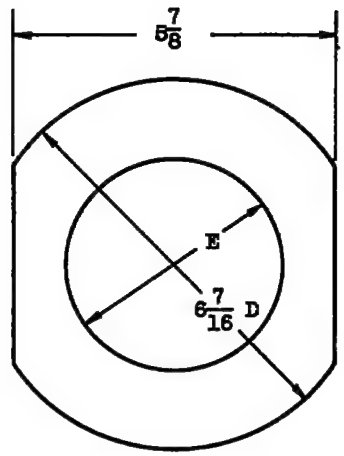
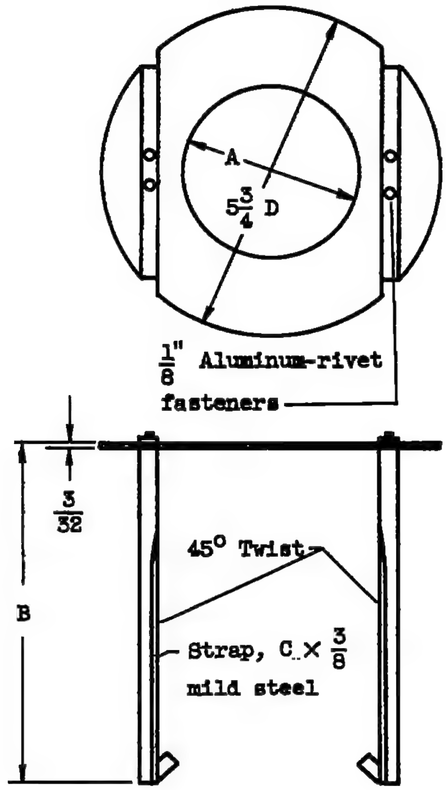


(b) Nozzle-mounted disk.

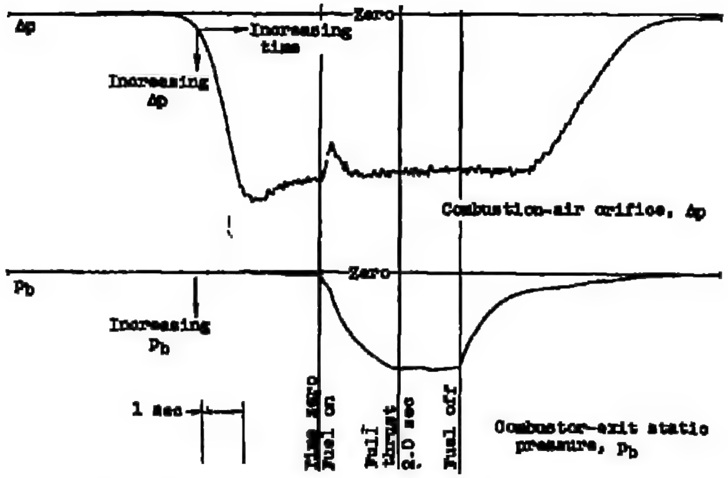


(a) Flame-holder-mounted disk.

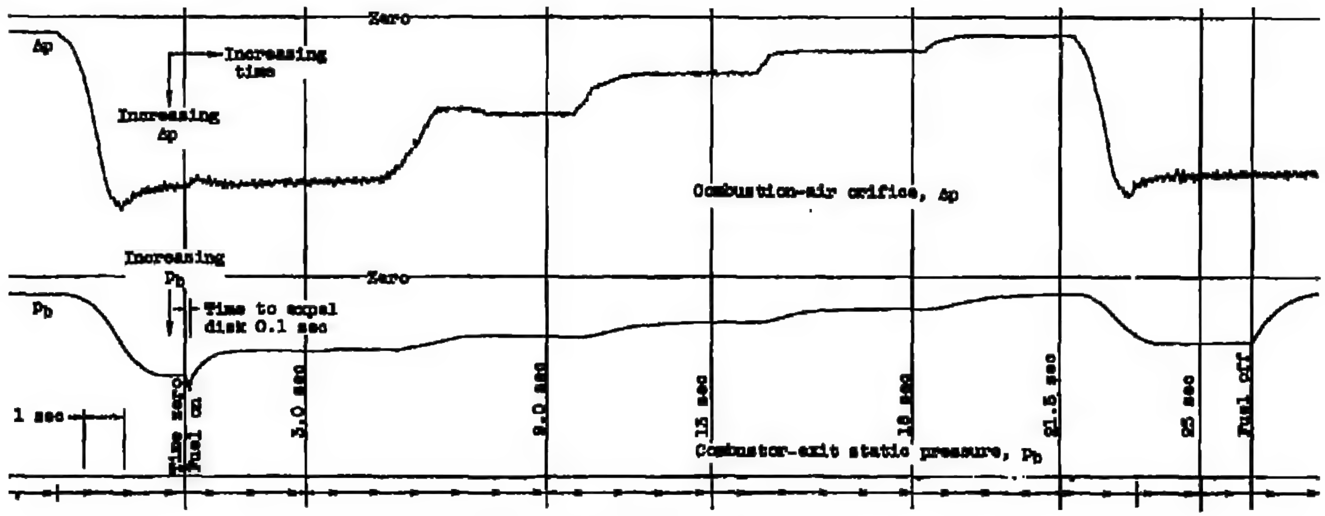
Disk	A	B	C	E	Number of fasteners	Disk material	Blocked area, percent[a]
1	2	6	$\frac{1}{16}$	--	2	$\frac{3}{32}$" Al 52S	69
2	2	6	$\frac{3}{32}$	--	2	$\frac{3}{32}$" Al 52S	69
3	2	10	$\frac{3}{32}$	--	4	$\frac{3}{32}$" Al 52S	69
4	3	10	$\frac{3}{32}$		4	$\frac{3}{32}$" Al 24S-T	57
5	-	--	--	4	-	$\frac{3}{32}$" Al 52S	62
6	-	--	--	$4\frac{1}{2}$	-	$\frac{1}{8}$" Al 24S-T	48
7	-	--	--	$4\frac{1}{2}$	-	$\frac{3}{32}$" Al 24S-T	48

[a]Percent of combustor area.

Figure 3. - Diagrams of starting disks.



(a) Flame-holder-mounted disk. Disk 6; run 23.



(b) Nozzle-mounted disk. Disk 7; run 31.

Figure 4. - Photographs of recorded data showing typical starting characteristics of 6.5-inch-diameter ram-jet engine with starting disks. Fuel, 50 percent magnesium powder in MIL-F-5624A grade JP-4.

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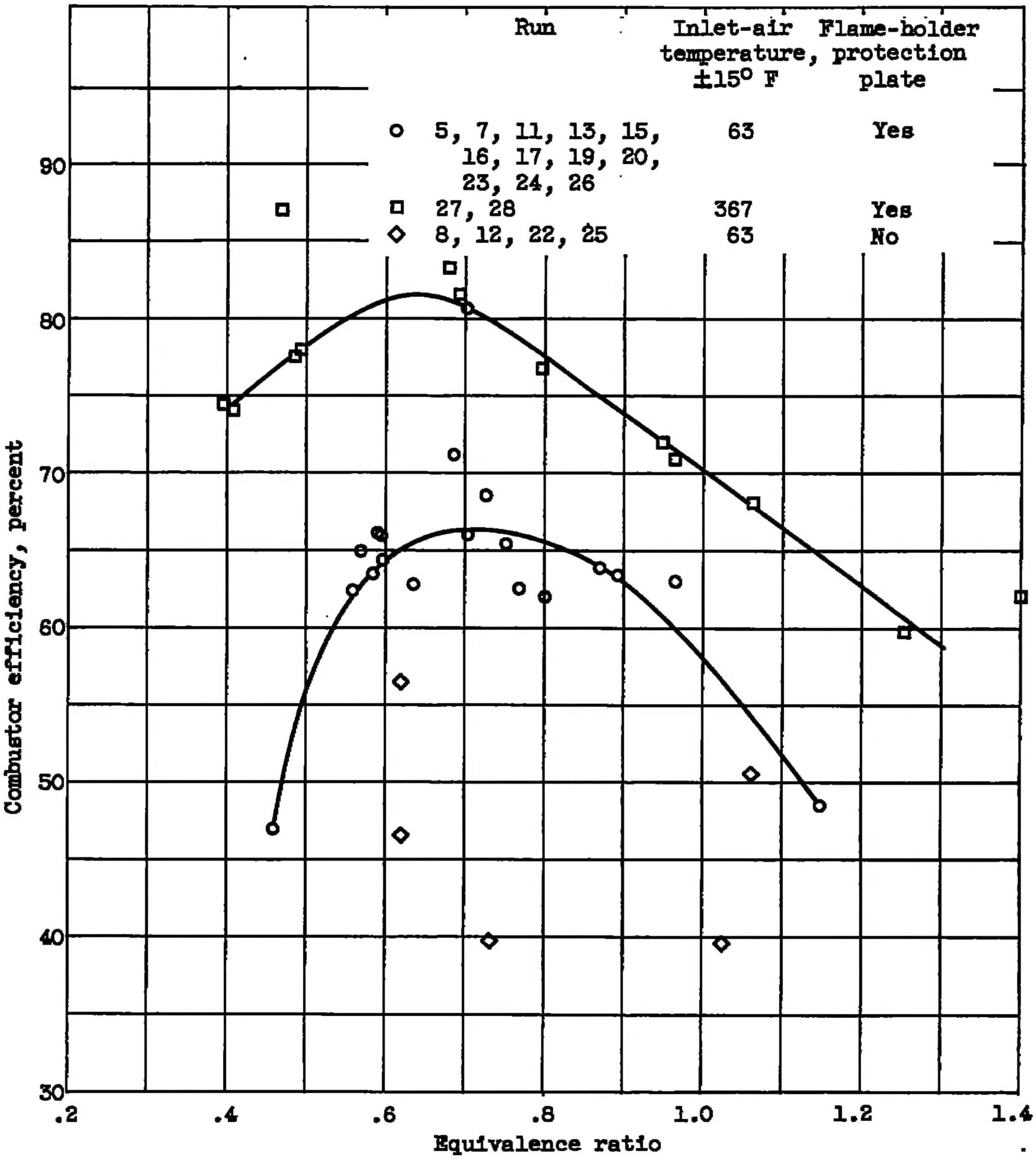

Figure 5. - Effect of inlet-air temperature and flame-holder protection plate on combustor performance. Fuel, 50 percent magnesium in MIL-F-5624A grade JP-4; fuel-distribution control sleeve, 2 inches long and 4 inches in diameter; fuel-air mixing length, 8.5 inches.

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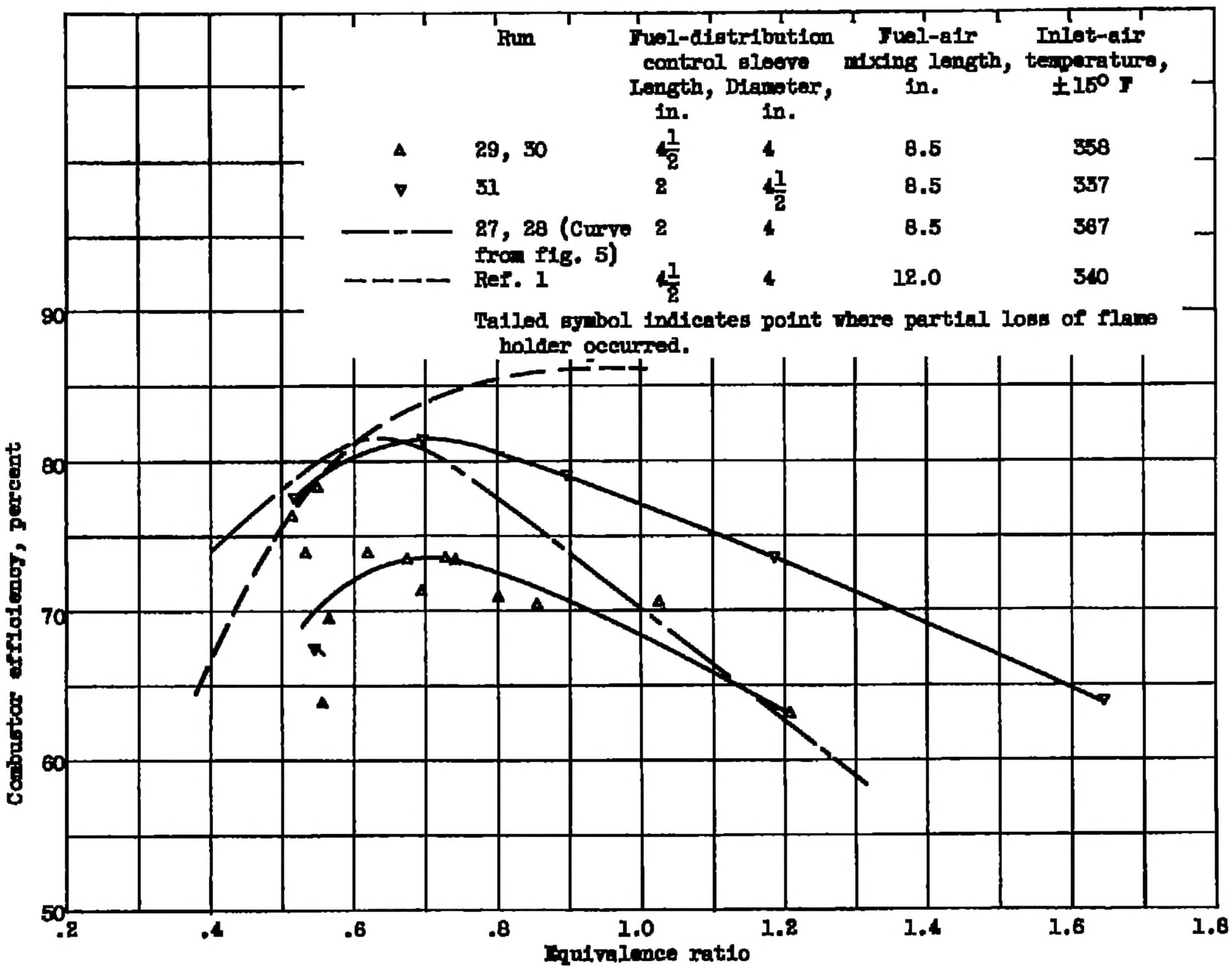

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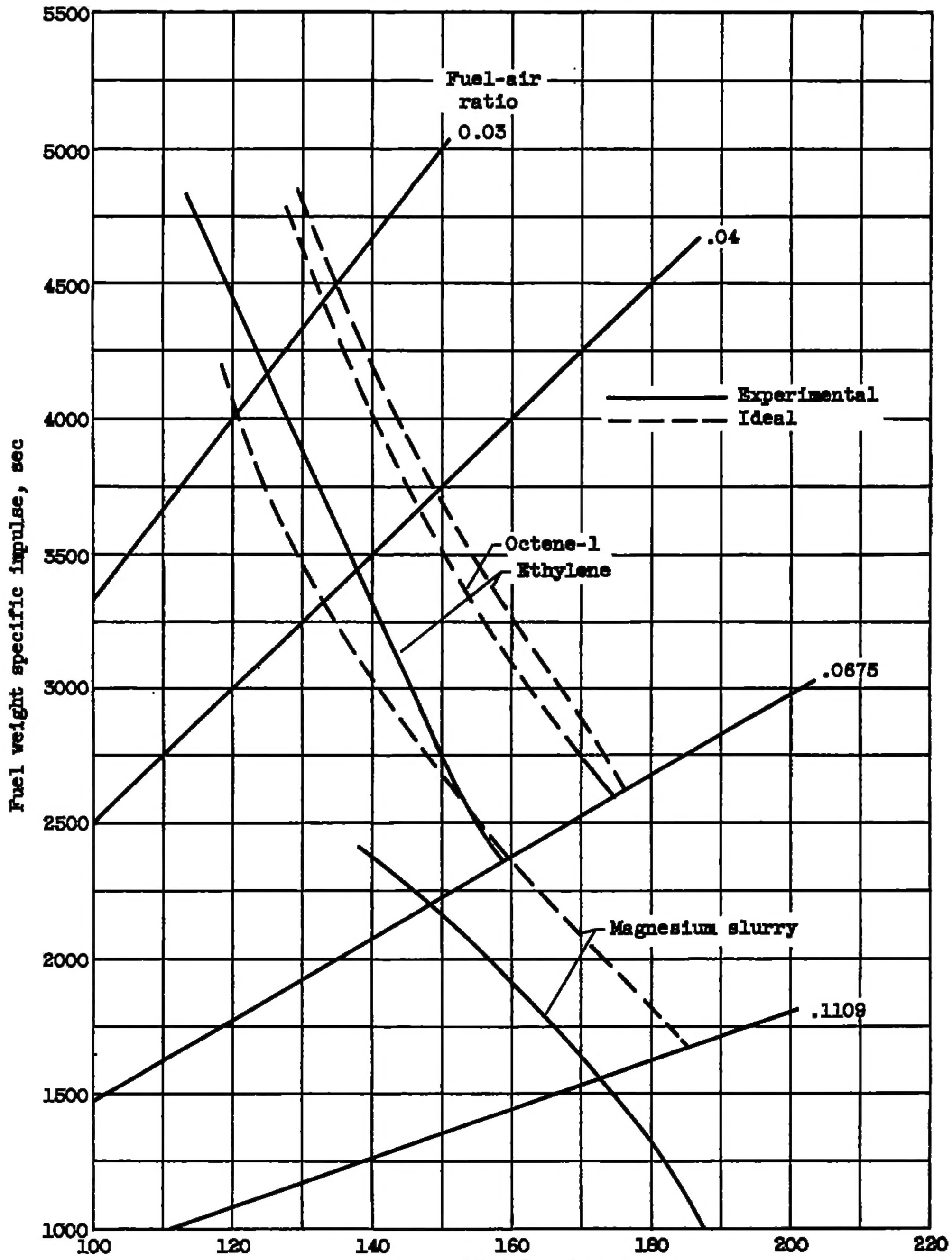
Figure 6. - Effect of fuel-distribution control-sleeve length and diameter on combustor performance. Fuel, 50 percent magnesium in MIL-F-5624A grade JP-4. Flame-holder protection plate incorporated.



(a) Fuel weight specific impulse as function of air specific impulse.

Figure 7. - Comparison of impulse data for three fuels. Combustor-inlet stagnation temperature, 350° F; sonic discharge of exhaust products. Experimental slurry data obtained from run 31 of figure 6 and experimental ethylene data obtained from reference 2.

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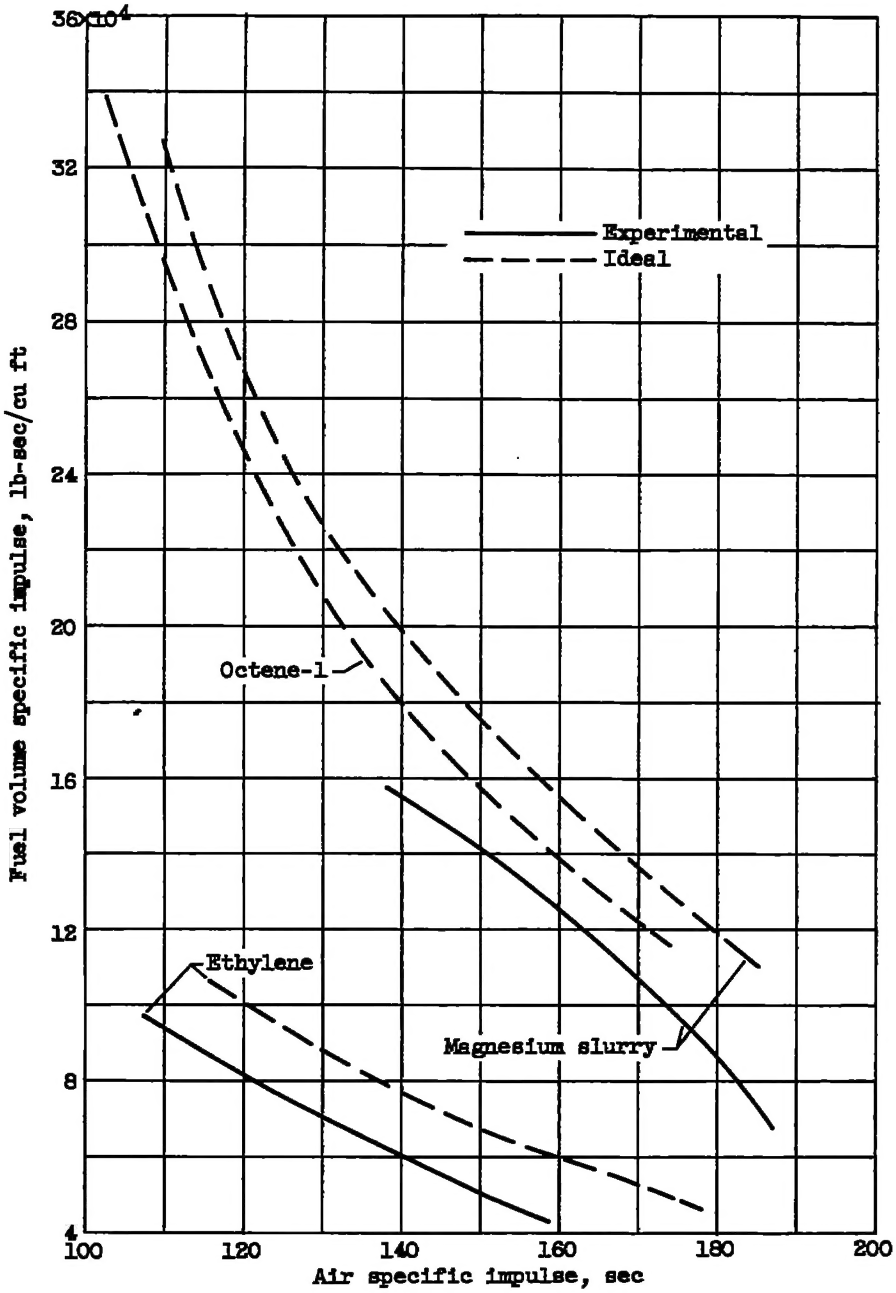

(b) Fuel volume specific impulse as function of air specific impulse.

Figure 7. - Concluded. Comparison of impulse data for three fuels. Combustor-inlet stagnation temperature, 350° F; sonic discharge of exhaust products. Experimental slurry data obtained from run 31 of figure 6 and experimental ethylene data obtained from reference 2.

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